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Developing Knowledge and Understanding for Autonomous Systems for Analysis and Assessment Events and Campaigns

by Jayashree Harikumar and Philip Chan

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14. ABSTRACT

This report presents an overview of adaptive autonomous systems and challenges posed to the analysis and assessment of those systems. Definitions, present systems under development, early attempts at taxonomy, and analysis metric definitions are reviewed. Sensor, fusion/logic, and actuator subsystems are defined for the purpose of analysis, and some subsystem analysis methods are suggested. Direct and indirect challenges to analysis are discussed. Important considerations associated with the doctrine, and tactics, techniques, and procedures that influence analysis and assessment are also discussed.

15. SUBJECT TERMS

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1. Introduction

Autonomous defense systems are of growing importance to the Army; the Deputy Secretary of Defense has identified autonomy as the critical technology in the Department's Third Offset Strategy (Ahner and Parson 2016). These systems can greatly aid the Warfighter yet pose challenges to system developers and system analysts.

There are many challenges in developing complete performance ontologies and test methodologies to define and evaluate the performance of autonomous systems. Chief among them is the dynamic environment in which the autonomous system is expected to operate. Change in the autonomous system's environment is expected to affect system performance. Test methodologies will have to include all aspects of this dynamic environment.

1.1 Background

Automation and autonomy offer significant military value in reducing danger to Warfighters, in increasing the speed and accuracy of time-critical operations, and in reducing the supervisory burden of Warfighters and control systems.

Autonomous systems can vary from simple adaptive automatic systems that are designed to operate in highly structured environments to fully self-governing systems designed to perform in highly dynamic and complex environments. Most Army autonomous systems are expected to range from automatic to semi-autonomous regimes.

1.1.1 Automated Systems

Automated systems are systems that require little or no human involvement for performing well-defined tasks with predetermined responses. The system responses of automatic systems are generally rule-based and are designed to operate in well-structured environments with few parameters. Automated systems can be adaptive through the use of environmental sensors and rule-based adaptation. An example of an automatic system is a laundry machine that adapts to different laundry loads.

1.1.2 Autonomous Systems

Autonomous systems are characterized as self-governing toward accomplishing their mission. System self-governance reduces the burden of control on the operator, allowing him or her to perform other tasks. Autonomous systems can be broadly classified by their level of autonomy:

- *Semi-Autonomous Systems* perform limited control activities to react to changes in the environment. Automated and semi-autonomous systems overlap in well-structured environments. An example of a semi-autonomous system is a self-navigating vacuum cleaner that can recognize and maneuver around obstacles.
- *Nearly Full Autonomous Systems* can perform many automated tasks, but the automatic functions are still activated or deactivated by an operator. These systems, when activated, can function without the control of an operator but lack some of the adaptability and decision making of a fully autonomous system. An example of a nearly full autonomous system is a self-driving car that can maneuver around obstacles, sense and interpret street signs and traffic lights, and choose the best course to its destination.
- *Fully Autonomous Systems* require no human intervention to perform tasks, even in drastically changing environments. A fully autonomous system assesses the environment and adapts to it to complete its mission. An example of a fully autonomous system is a deep-space probe expected to complete its mission without communication from Earth.

1.1.3 Unmanned Systems

Unmanned systems (UMSs) do not have a human driver/operator on board the system and can range from remote control to fully autonomous systems.

1.1.4 Adaptive Systems

An adaptive system can make changes in its performance according to its state, the environment it finds itself in, and a changing mission. Adaptive systems can range from being automatic to fully autonomous. Adaptive systems can be a set of discrete interacting, interdependent, real, or abstract entities that react together to environmental changes or changes in system status. A distributed adaptive system is a system in which an understanding of the individual parts does not necessarily convey an understanding of the whole system's behavior.

The modern battlefield has automated and various levels of autonomous systems working together in a complex, unstructured, operational environment. Future battlefields are expected to have an increased number of autonomous systems working together or independently on shared or independent missions.

1.1.5 Intelligent Systems

Intelligent systems are machines with embedded logic that can gather, interpret, and analyze data (i.e., the ability to reason) and communicate with other systems.

An intelligent system can choose the correct behavior for the completion of its mission but is bounded by its capability. Intelligent Control Systems are usually equipped with sensors to gather data from the environment, sensor processors to fuse the collected data and create a world model, and decision making processes to issue commands toward performing assigned tasks.

1.1.6 Ongoing Autonomy Programs

Ongoing autonomy programs are presented in Table 1. These programs illustrate that autonomous defense systems have to operate "intelligently" in unstructured, dynamic environments. The primary challenge in testing these systems is the broad scale, complexity, and adaptability of the autonomous behavior, missions, and operating conditions.

Table 1 Ongoing autonomy programs

Program	Domain	Description	Reference
Loyal Wingman	Air	Unmanned aircraft in cooperation with a manned aircraft expected to accomplish mission and return safely.	RFI-AFRL-RQKH-2015-003.pdf
DARPA CODE	Air	Unmanned aircraft with CODE software expected to find and engage targets in cooperation with other CODE-equipped systems.	http://www.darpa.mil/program/collaborative-operations-in-denied-environment
ACTUV	Sea	Anti-Submarine Warfare Continuous Trail Unmanned Vessel (ACTUV) is an unmanned vessel optimized to robustly track quiet diesel electric submarines.	http://www.darpa.mil/program/anti-submarine-warfare-continuous-trail-unmanned-vessel
SAFFiR	Sea	Shipboard Autonomous Firefighting Robot (SAFFiR) is a human-sized autonomous robot capable of finding and suppressing shipboard fires and working seamlessly with human firefighters.	https://www.onr.navy.mil/en/Media-Center/Fact-Sheets/Shipboard-Robot-Saffir.aspx
AMAS	Land	Autonomous Mobility Applique System (AMAS) is an autonomy kit for military logistics vehicles that provides driver warning/driver assist and leader-follower capabilities with a path to full autonomy. The AMAS is a multi-platform kit integrating low-cost sensors and control systems onto military vehicles to enable autonomous convoy operations.	https://www.lockheedmartin.com/us/products/amas1.html https://www.military.com/defensetech/2017/03/30/driverless-convoy-technology-fielded

Table 1 Ongoing autonomy programs (continued)

Program	Domain	Description	Reference
AGR	Land	Autonomous Ground Resupply (AGR) consists of autonomous resupply vehicles for Army use in resupply missions.	VAAT (FY17) https://www.dvidshub.net/video/553637/tardec-demonstrates-autonomous-ground-resupply-science-and-technology-objective
ExLF	Land	In Expedient Leader-Follower (ExLF) the lead vehicle in a convoy is manually driven, and the following vehicles in the convoy receive data and commands from the lead vehicle.	ASA(ALT) program

1.2 Purpose and Payoff, Goals, and Deliverables

1.2.1 Purpose and Payoff

The Artificial Intelligence and Machine Learning Essential Research Programs to Help the Army of 2050 (Perconti 2017) directly supports the US Army Research Laboratory's Key Campaign Initiative (KCI) for developing and understanding autonomous systems. The broad purpose and payoff given with this KCI are as follows:

- **Purpose**: Develop a knowledge and understanding framework for the analysis and assessment (A&A) of autonomous systems, including systems incorporating artificial intelligence (AI) and machine learning.
- **Payoff**: Provide the knowledge and understanding to develop tools, techniques, and methodology to perform A&A of autonomous systems and autonomous system designs that include systems that incorporate AI and machine learning.

1.2.2 Goals

The principal goal of this project is to provide ARL's Survivability/Lethality Analysis Directorate the ability to perform A&A of autonomous systems and autonomous system designs to support the test and evaluation (T&E) and analysis community, as well as individual customers. This includes systems that incorporate AI and machine learning.

The key goal was refined into four tasks:

- Identify the challenges and problem-space for the A&A of autonomous systems.
- Identify questions that need to be answered to perform the A&A of autonomous systems.
- Identify important considerations associated with the doctrine and tactics, techniques, and procedures (TTPs) that influence A&A of autonomous systems.
- Develop key metrics and measures to perform A&A of autonomous systems, including systems incorporating AI and machine learning to support the T&E, analysis community, and Department of Defense customers.

1.2.3 Deliverables

The deliverables or capabilities needed for this effort are key metrics and measures that can be used to evaluate new (modern) technologies and systems with varying levels of autonomy working together in a complex operational environment. These come in the form of measures of performance and measures of effectiveness.

2. Challenges and Problem Space for A&A

Autonomous systems are designed to learn and operate in uncertain and dynamic environments with other autonomous systems of similar and dissimilar design. A key challenge in analyzing these systems is that they "think" differently than humans and thus may be vulnerable in different and unexpected ways.

Autonomous systems are often designed with open architectures and similar interoperability standards to promote modularity for reuse and may share similar perception and cognition systems. One consequence of this design method is that system susceptibilities can be common to different autonomous systems, and adversaries can take advantage of the same shortcomings on different autonomous system platforms.

The challenge space for testing autonomous systems can be broadly classified as direct, indirect, distributed, and human–autonomous system interaction challenges.

2.1 Direct Challenges

Direct challenges relate to testing the "known" response to the autonomous system. These tests evaluate whether the autonomous system

- exhibits emergent behavior that is within "normal" acceptable operational range for the given mission,
- adapts to the "right" (local, global) parameter value sets to complete mission goals,
- has an acceptable self-determination of normal state, and
- can recover to normal state within a reasonable amount of time.

2.2 Indirect Challenges

Indirect challenges include evaluating autonomous system response in unknown situations to determine if the response is within the known response set for the autonomous system. The problem space for these tests are

- autonomous system use in new or scaled missions, and
- autonomous system integration with other homogeneous systems in larger missions.

With both direct and indirect challenge problem spaces, the system response space is relatively bounded; that is, the situation within which the autonomous system is intended to function is known. Additionally, the overall system is homogeneous in the sense that that autonomous system is the only autonomous element present.

2.3 Distributed Challenges

Distributed challenges are T&E challenges that result from the following:

- Different autonomous systems working with each other as a cluster of autonomous systems or as an organization of autonomous systems, each with different functions
- "Social" adaptation
- Hierarchical behavior
- "Friend or foe" determination
- Detection of abnormal behavior of other elements

2.4 Human-Autonomy Challenges

Autonomous system interactions with humans involve challenges associated with the human trust of the system decision making, human response to the autonomous system behavior, and challenges with evaluation of this trust. (This report does not address the hurdles associated with the human trust of autonomous systems.)

Distributed and human-autonomy challenge space address interactions with heterogeneous systems and how those interactions evolve. These interactions can grow unbounded since the outcomes are not mapped back to a set of bounded issues, as was the case for direct and indirect challenge test space.

3. Questions That Need To Be Answered to Perform A&A

Most survivability analysis work is focused on potential enemy threats. With autonomous systems, as discussed in Section 2, the evolution of the outcome system space needs to be understood. Also, other questions that require answers include understanding the impact of operating the autonomous system on the Warfighter. We believe that the following questions need to be addressed to develop a knowledge framework to autonomous system A&A:

Q1: Autonomous system behavior may change continuously as it makes decisions and learns from its sensor data and intermediate goal outcomes. How can the analyst distinguish/separate perception and reasoning for learning systems?

Q2: How can the tester define test adequacy when evaluating a non-deterministic learning system with an infinite and continuous factor and decision space?

Q3: How does one quantify the success of decision making?

Q4: How does one measure learning?

Q5: How can tests adapt in real time as the autonomous system under test readjusts to the environment, and its autonomous system and human agents?

Q6: What is the operational ease of use of the autonomous system for the Warfighter?

Q7: What level of learning is required to operate the autonomous system?

Q8: How do we quantify the level of distraction to the Warfighter using the autonomous system?

Q9: What is the differential advantage in using an autonomous system (comparative analysis of survivability benefits gained about new vulnerabilities introduced by the autonomous system)?

The next set of questions deal with uncertainty in environment and uncertainty in the decision making of autonomous systems:

Q10: What is the stability of the autonomous system's normal state? Autonomous systems interact with the environment and other autonomous systems. These interactions could define a new regular state for the autonomous system. How dynamic is the autonomous system's normal state?

Q11: How stable is the autonomous system's recovery from an abnormal state?

Q12: Given the learning behavior of the autonomous system, what is the time required for the autonomous system to regain its normal state after it is perturbed by the environment? What is the time required for the autonomous system to define a new normal phase after the environment has changed?

Q13: What is the expected frequency and magnitude of abnormal, destabilizing, or "outlier" events?

4. Separation of Subsystems for Testing

Autonomous systems are made up of three distinct subsystems that can be analyzed and assessed separately before the whole autonomous system undergoes testing. Separate testing of these subcomponents can simplify the A&A effort as well as help identify the causes of system failure.

The first subsystem to be analyzed is the sensors of the autonomous system. Since these sensors connect the autonomous system to its surroundings, their sensitivity, resolution, and adequacy should be examined against the autonomous system's mission needs. These tests can be as easy as design specification analysis and individual sensor bench testing.

The second subsystem to be analyzed is autonomous system's logic circuits and AI. These circuits and AI use sensor data to form an understanding of the autonomous system's environment and to effectuate its mission within this environment. Testing depends on the type of AI used. Discrete AI systems can be tested using ontological analysis, while continuous-state AI systems are generally tested during training (e.g., the standard tenfold cross-validation approach used in artificial neural network AI).

The third subsystem that can be independently analyzed is the actuator subsystem. This subsystem can be design and bench tested, comprising analysis of individual actuator, and combined or complete actuator tests.

Once these subsystems have been tested, subsystem combinations can be tested on the bench or on a hardware-in-the-loop system. For example, the sensor and AI portions can be tested for correct input into the actuators.

The complete autonomous system will still need to be analyzed and assessed in realistic scenarios because of the presence of decision-making logic and learning algorithms that change the autonomous system state with changes in environment and experience (learning) levels. Numerical analysis of the autonomous system simulations can be used to systematically analyze the possible environmental and mission scenarios and their combinations.

5. Important Considerations Associated with the Doctrine and TTPs That Influence A&A

Army doctrine is the fundamental military principle by which military forces or elements guide their actions in support of national objectives. TTPs incorporate the Army's evolving knowledge and experience. They support and implement fundamental principles, linking them with associated applications and the "how to" of TTPs. There are emerging TTPs for the autonomous system, but if it were to follow these TTPs, there would be a need to redesign some of the US Army strategies in both defense and attack. The modern battlespace consists of complex adaptive systems working with autonomous systems and autonomous intelligent systems (Warfighters). The human Warfighter is always working toward success in the final mission, and his actions are largely governed by TTPs and doctrine. An artificially intelligent system, on the other hand, mainly responds to its environment by fusing and interpreting data it gathers from its sensors and knowledge banks. A significant difference that needs to be considered is, can the autonomous system operate in ways that are not conducive to mission success? For example, the autonomous system making an unintended noise and alerting the target when the Warfighter is surveying a target unobserved.

The answer possibly lies in understanding how the adaptation occurs. If the locus of adjustment is internal to the system, the autonomous system response space is relatively bounded and the autonomous system behavior will be sufficiently predictable to determine if the behavior is conducive to mission success. On the other hand, if the Warfighter/human operator can introduce a new capability, or extend the existing capacity of the system, the locus of adaptation for the autonomous system will be external to the system, and the autonomous system can operate in ways that are not conducive of mission success.

6. Measures and Metrics That Can Be Used to Evaluate Autonomous Systems

The ability of a system to make choices (plan) and then act (decide) on the choice makes it autonomous. There are engineering and system-level metrics and measures that are used by combat developers, the T&E community, and PMs to verify and validate the individual systems in an operational environment. However, there is a paucity in measures and metrics that evaluate "friendly" systems' responses to environmental changes and adversarial threats. A possible reason for the lack of measurements can be the Warfighter's expectation that the autonomous system operate within a well-defined scope of autonomy, and the Warfighter have insight to the learning ability, intelligence, and capability of the autonomous system. We suggest the following measures and metrics to qualify and perhaps quantify these (learning ability, intelligence, and capability of the autonomous system) attributes.

6.1 Metrics to Assess Autonomous System Behavior Response to Changes in Environment

When a change in the environment makes an autonomous system change its behavior, it can *sometimes* be an autonomy affecting factor (Barber and Martin 1999; Hrabia et al. 2015). Exemplar measures are shown in Table 2.

Table 2 Exemplar measures to assess the autonomous system response behavior

Measure	Metric
Number of times the system changed its behavior because of a change in environment	Autonomy behavior
Number of times the system behavior change was restricted by outside control	Autonomy control
Number of times the system took an action that was similar to a subject matter expert response	Trust Quality
Response time of the autonomous system to the change	Autonomous system capability to perform autonomously in uncertain environment

6.2 Metrics to Assess the Autonomous System Intelligence

An autonomous system will change its decisions with time, by virtue of its learning, and in time might respond differently to the same stimulus in the same environment. Since the change in system response is due to the change in system learning, it is necessary to measure the system intelligence at regular intervals to determine the possible action space of the autonomous system. Some examples to assess autonomous system intelligence are shown in Table 3.

Table 3 Exemplar measures to assess autonomous system intelligence

Measure	Metric
Could the system perform its tasks in unstructured environment (Yes/No)	Autonomous system intelligence
Number of steps the autonomous system took to complete the task	Autonomous system learning
Time taken by autonomous system to complete task	Autonomous system learning
Autonomous system response in a different scenario	Autonomous system metric focused on learning (intelligence)
Attributes to compare system response taken to the "preferred" system response	Differential advantage System intelligence

6.3 Metrics to Assess the Autonomous System Capability

Autonomous system capability is not autonomous system intelligence; intelligence is the ability (of the system) to develop a good solution to a problem, which will maximize the likelihood of goal success in a dynamic and uncertain environment, whereas capability is the ability to successfully execute the action (Gunderson and Gunderson 2004). An autonomous system that can generate multiple subtasks to achieve a goal but can only implement a single choice is more intelligent than an autonomous system that can produce fewer subtasks but can perform more than an individual decision. The latter autonomous system is a more capable system, but both systems are autonomous. The dynamic behavior of a system is bound by the system's intelligence and capability. In a complex operational environment, if the system intelligence is not matched with its capacity, the system behavior will be unpredictable. On the other hand, if system capability exceeds system intelligence, the system will be underutilized. Table 4 provides exemplar measures to assess autonomous system capability.

Table 4 Exemplar measures to assess autonomous system capability

Measure	Metric
Analyze the choice set made by the autonomous system prior to the autonomous system response.	Determine if choice of action was limited by autonomous system intelligence or capability.
Compare system response to the original set of capabilities developed for the autonomous system.	Determine if the human operator introduced a new capability or modified an existing capability.

Performance metrics to assess autonomous systems in dynamic domains have to consider both intelligence and capability together in its reasoning.

6.4 Other Measures and Metrics

Table 5 shows other measures and metrics that may be used in autonomous system testing.

Table 5 Other measures and metrics

Measures	Metrics
Terrain irregularity (Entropy measure environment uncertainty)	MOP related to system tracking error along a planned trajectory in a system space
Information loss/delay	MOP of system autonomy
System reaction time (average, min, max)	MOP of autonomous system capability to perform autonomously in uncertain environment
System action taken	MOP of scenario uncertainty contributed by the adversary unexpected and unknown reaction
Learning rate	Weighted sum of learning from saved historic data and temporal update rate
Number of steps autonomous system takes to achieve goal versus steps that will be taken by a human operator	Metric will be dynamic if system goal changes with time
Allowed system response time to the actual response time of system	Differential advantage
Attributes to compare system response taken to the "preferred" system response	Metric to determine differential advantage Metric to assess system intelligence Metric to assess system capability
Measure of information needed by a human agent to select the next TTP in the presence and absence of an I-AS	Survivability metric to measure the cognitive workload of the human operator

6.5 Other Measures and Metrics Models in Literature

6.5.1 Autonomy Levels for Unmanned Systems (ALFUS)

The ALFUS framework (model) was developed by the National Institute of Standards and Technology (Huang et al. 2005) to categorize autonomous systems in generic and metric-based terms. The ALFUS framework (Fig. 1) was based on a three-axis model comprising the Mission Complexity, Environmental Complexity, and Autonomy Level axes.

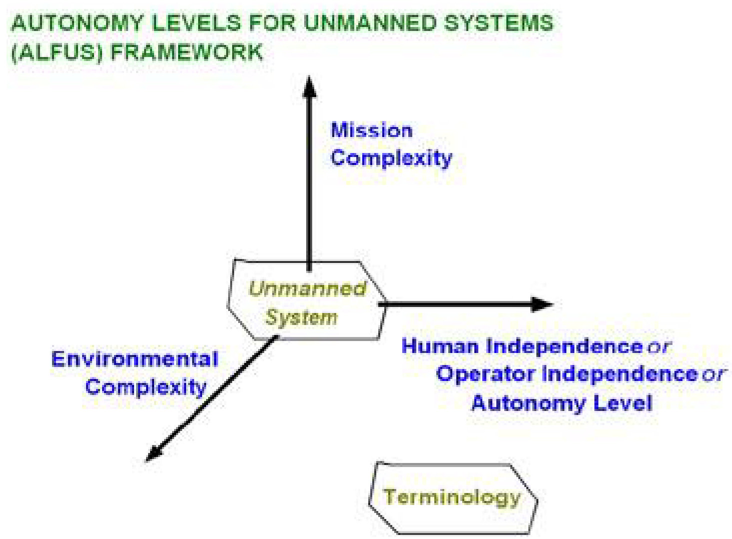

Fig. 1 ALFUS framework

It was a good first attempt at classifying various autonomous systems. The triaxial model was relevant as it attempted to categorize an autonomous system using different complexity dimensions. Some issues associated with the ALFUS triaxes model were correlation and interdependency (axes overlap), unconsidered axes such as system performance, and nominal versus instantaneous performance (Huang et al. 2005). ALFUS is a good start to autonomous system classification, and it could be useful in deciding what type of testing will be required for A&A. Still, a substantial amount of additional development will be required to use ALFUS as a standard for autonomous system classification.

6.5.2 Performance Measures Framework for Unmanned Systems (PerMFUS)

PerMFUS is a multiaxis performance metrics model for UMSs. The model characterizes the UMS performance requirements by the missions that are to be carried out, the environments in which the missions are to be performed, and the characteristics of the UMS itself. The main aspects of PerMFUS are the three-axis model (Fig. 1); the set of performance areas to be focused on, such as mobility/ navigation, sensing/perception, energy/power, communication, human-system interaction, end-effector, collaboration/coordination, and payload; approach on how the UMS's hardware and software characteristics contribute to the UMS performance; and an initial set of generic environmental characteristics and an initial set of generic metrics. Autonomy is considered an aspect of UMS performance.

The main idea behind PerMFUS is that metrics must be associated with certain UMS contexts to be meaningful. There are many types and layers of contexts that can be associated with metrics, and the paper by Huang et al. (2010) provides a sampling of these metrics.

7. Conclusions

In this report, we have identified some of the questions that need to be answered to perform the A&A of autonomous systems and have provided a few key metrics and measures to develop an analysis framework. The measures and metrics only provide a starting point to an analyst wishing to A&A autonomous system.

Autonomous defense systems are expected to operate in unstructured dynamic environments along with human Warfighters and other autonomous systems at varying levels of autonomy. By design, the autonomous system is supposed to learn and adapt, which presents a challenge in testing the system. The problem is further amplified when the system intelligence exceeds its capability, leading to unpredictable behavior that can alter the environment for all systems operating with the rogue autonomous system. There is a need to also consider the following components within the autonomous system for in-depth and thorough analyses:

- Sensor and actuator limitations and their effect on the autonomous system
- Impact of decision deficiencies on the autonomous system mission
- Sensor ambiguity on AI system
- AI learning and learning rate limitations
- Effect of nonstationary environment and adversaries

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List of Symbols, Abbreviations, and Acronyms

A&A	analysis and assessment
ACTUV	Anti-Submarine Warfare Continuous Trail Unmanned Vessel
AGR	Autonomous Ground Resupply
AI	artificial intelligence
ALFUS	Autonomy Levels for Unmanned Systems
AMAS	Autonomous Mobility Applique System
ASA(ALT)	Assistant Secretary of the Army (Acquisition, Logistics and Technology)
ExLF	Expedient Leader-Follower
KCI	Key Campaign Initiative
MOP	measures of performance
PerMFUS	Performance Measures Framework for Unmanned Systems
SAFFiR	Shipboard Autonomous Firefighting Robot
T&E	test and evaluation
TTPs	tactics, techniques, and procedures
UMS	unmanned system

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